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FUEL-FAILURE DETECTION IN LMFBR POWER PLANTS

by

K. G. A. Porges

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Reactor Physics Division

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ABSTRACT

LMFBR plants now under design impose new requirements on fuel-failure detection: In addition to detection systems that are essentially diagnostic and therefore can trade speed for sensitivity, equipment must be provided that can effect the fastest possible shutdown in case of a major failure. This report is primarily concerned with the application of delayed-neutron monitoring to the latter task. The various effects on the signal obtained from such a channel of the type of fuel, conjectural failure mechanism, fission-product transport to the detector site, and, finally, electronic processing are discussed and evaluated in the light of transient-detection statistics. Such statistical considerations strongly emphasize the need for adequate electronic processing and provide guidance in the choice of detector site and other hardware decisions. With well-designed electronics and a favorable site, a delayed neutron-monitoring system can give a failure indication within about 5 sec from the actual moment of failure, whereas a flowmeter gives an indication within 1 sec from the moment the channel becomes blocked by debris. The delayed-neutron signal should allow certain inferences regarding the type and extent of failure from the signal shape; the flowmeter, on the other hand, locates the event. The two systems thus complement each other.

I. SUMMARY

The rapid and reliable detection of fuel-cladding failures in future large power reactors of LMFBR (Liquid Metal Fast Breeder Reactor) type presents a number of problems that appear to require discussion, even though many plant design parameters are still uncertain at this writing.

At the outset of such a discussion, let us distinguish between different types of cladding failure, which we may call "leaks" and "bursts." The appearance of cladding leaks in LMFBR plants does not imply a serious and immediate hazard *per se*. However, equipment is usually provided to indicate cladding leaks through the presence of fission products in the coolant or gas blanket. Various types of detection systems have been developed for this task in connection with other reactor designs; some of these are being tested on existing LMFBR facilities such as EBR-II (Experimental Breeder Reactor-II). Novel ideas, chiefly aimed at facilitating the location of a failed element or subassembly, have been proposed and still require testing. On the whole, the technical development of cladding-failure detection for diagnostic purposes in connection with LMFBR plants may be said to be well advanced.[1-7]

In contrast, the prospect of coping with possible violent bursts in time to prevent further damage to the core is somewhat doubtful. The high power density and high cladding surface temperature characteristic of the LMFBR design require a very large coolant throughput. Consequently, blocking of a flow channel by debris (such as might be thrown off by a burst) can be estimated to lead to proliferation of damage within seconds, depending on the degree of blocking. Thus far, the only practical means envisaged of detecting flow obstruction rapidly enough to at least limit the likely damage is direct flowmetering of each subassembly. Temperature readout at many points, which has long been the mainstay of safety instrumentation, is comparatively slower; it is thus useful mostly for confirmation. All other practical methods entail still more delay.

It may now be pointed out that flowmeter and temperature indications start at the moment the channel is actually blocked, and thus do not react to the preceding chain of events, involving a cladding burst and expulsion of debris. The onset of those phenomena, whatever may be their duration and complexity, is connected with the injection of fission products into the coolant--among others, delayed-neutron precursors (DNP's). Fission-product detection by a downstream DNP monitor is inevitably delayed by the transport time, which cannot be reduced below a few seconds. By itself, such a monitor is evidently not to be relied upon to prevent all damage; however, the transport delay counts from the moment of rupture, while other indications depend on somewhat later occurrences. A DNP monitor would thus complement the flowmeters and thus contribute significantly to overall plant safety, particularly for events that feature some delay between burst and channel blockage, or when debris is emitted but does not immediately block the flow (in which case it may still lodge elsewhere in the core in a subsequent passage). The present status of experience with cladding bursts does not rule out such conjectural failure histories.

DNP monitoring is further useful in connection with the detection of small leaks, or similar essentially diagnostic tasks. DNP systems that do <u>not</u> aim at the fastest possible detection are, in fact, employed largely for that purpose. However, although several other schemes can detect the presence of fission products in the coolant or gas blanket with comparable, or perhaps greater, sensitivity, no other method has the potential for detection of a major failure with minimum delay, as discussed in full detail in another report on the subject of fast-transient detection.[1] To exploit this potential, a detector site directly on a main coolant duct is required. For various practical reasons, however, existing DNP monitors (such as the FERD--Fuel Element Rupture Detector-- system of EBR-II) are located on bypass loops. This report discusses the pros and cons of these two types of detector locations, without entering into specific design features (which would depend in large measure on other design details of the reactor plant). One of the important advantages of a "close" site (aside from minimum announcement delay) is the improvement of detection statistics. This results, on the one hand, in improved reliability, and on the other hand, in a clearer "signature" through which the type of failure can be inferred.

The statistics of detection[2] are generally emphasized here, since statistical considerations provide the key to rational equipment design. Thus, for instance, the dependence of such indices of reliability as the detection probability on the signal^2/noise ratio has certain important implications for the design of shielding.

Another point that needs some emphasis is the design and adjustment of electronic signal-processing equipment. The possibility of recognition of certain types of cladding failures (which is likely to become a more important aspect of DNP monitoring as more information regarding the mechanism of failure becomes available) depends in large measure on the frequency-response bandwidth of the processor. In this connection, the usual combination of a general-purpose count-rate meter and chart recorder is entirely unsuitable for either reliable detection or signature recognition, considering that the equipment is required to portray transients of a peak width amounting to a fraction of a second.

To sum up, the main conclusion of this report is the contention that a fast-responding DNP installation can contribute significantly to the safety of an LMFBR power plant. To make such an installation effective, beyond its use as just another diagnostic device, hardware and shielding problems connected with a site on a main coolant duct will have to be solved, and an electronic signal processing system (or computer software) adapted to the hardware system will have to be developed and tested.

Fuel-cladding failure-detection equipment is not subject to the normal test of practical performance which, for other newly developed instrumentation, quickly vindicates either the claims of the designer or the natural skepticism of the user. A given cladding failure-detection system may never be faced with a "catastrophic" cartridge burst during the entire operating life of the plant; progress in reactor design may render the system obsolete before it can be known whether its principle, or its detailed design, is sound. In this situation, technical progress is best promoted by detailed discussion and presentation of arguments, to which the present report is hoped to contribute.

II. INTRODUCTION

The design of a fuel-failure detection system, as well as the policy governing its ultimate use, should ideally be based on reasonably complete descriptive knowledge of the process of fuel failure. In particular, one would want to know the likelihood of different types of failures, and moreover be able to infer the degree of danger to the plant implied by each type, both as to extent and as to speed of development of damage. This kind of information is being actively sought through capsule tests in TREAT (Transient Test Reactor Facility) and similar tests elsewhere, and may be available when the fuel-failure system for some future power plant is designed. The general mission of this equipment and, in particular, the required speed of detection will then be clearly defined.

In connection with a number of LMFBR power plants now under design, the fuel-failure problem is usually treated in terms of heating and melting rates following an initial fuel-pin rupture which partially or fully blocks the coolant flow through its own channel. Some of those calculations[8] indicate that, in the event of total loss of flow, damage starts spreading within 1 sec to adjacent channels (for partial blockage, delay is correspondingly greater). Thus, even the fastest possible instrument reading cannot be guaranteed to prevent all damage. The only practical means of effecting a rapid enough shutdown to at least localize damage is direct sensing of the flow through each subassembly, together with temperature reading. Such sensing channels are accordingly provided. However, the history of the initiating event up to the point where channel blockage occurs remains largely uncertain. In particular, the first perforation of the cladding may occur some seconds before the entire fuel element disintegrates and debris lodges in the flow channel, probably at first partially and then possibly completely shutting off the flow. Moreover, debris can be thrown into the coolant without causing flow blocking well above the normal excursions in flow speed. Such an event would therefore be difficult to detect on the subassembly flowmeter, while still resulting in a significant hazard. This line of argumentation points to the need for a very fast-responding system which detects fission products and/or debris emerging from the core.

A previous survey of available detection systems[1] and similar surveys by other authors have indicated that where speed is essential, only delayed-neutron monitoring can provide the necessary background-rejection capability, in conjunction with sensitivity to a set of adequately short-lived fission products.* Other considerations, such as the difficult thermal and radiation environment in which the detection station must operate reliably with minimum maintenance, make it at least improbable that some new fission-product detection method will become competitive with DNP monitoring in the foreseeable future.

*This matter of speed is sometimes misunderstood since it applies only to sodium-cooled plants. For DNP fuel-failure monitoring in connection with water-cooled reactors, a transport delay must be introduced deliberately in order to promote decay of the well-known 4-sec delayed-neutron activity ^{17}N.

A DNP monitor is simply a bank of neutron detectors, shielded from core neutrons, which view some duct through which coolant flows after emerging from the core. The duct may be the main coolant pipe or a bypass loop; the types of neutron detectors available with reasonable detection efficiency also require some local moderation. Further details are given in the appendix.

This report concentrates on those parameters of a delayed-neutron monitor that affect its speed of response and reliability. In general, speed of response depends on the expected shape of the count-rate excursion delivered by the neutron detectors, as well as on the quality of signal processing--a matter that is stressed here since it appears to have been neglected in other discussions of the subject.

The shape of the count-rate excursion depends, in turn, on fuel design, as well as on the (speculative) detailed failure history. Specifically, sodium-bonded fuel, as discussed in Section III, may yield a rather characteristic "spike" in the channel count rate due to the emission of bonding sodium, highly enriched with fission products (inter alia, DNP's). The metallic driver fuel now installed in EBR-II is sodium-bonded; newer oxide fuel pins have generally abandoned bonding in favor of more tightly fitting cladding. The advent of carbide fuel, however, has led to the reintroduction of sodium bonding, to allow for dimensional changes in the fuel pins with good heat transfer. Thus, the present discussion, evidently inappropriate for oxide fuel, becomes practically significant for the most advanced fuel type now considered.

Aside from the spike signal one expects from the passage of the highly contaminated "slug" of bonding sodium, a particularly serious fuel failure, which throws a number of pieces of cladding and/or fuel debris into the coolant, should similarly result in a series of spikes, provided that the signal is processed with electronic equipment of adequate bandwidth. On the other hand, a crack in the cladding may open very gradually in time, eventually leaving an appreciable area of the bare fuel in contact with the flowing coolant. The resultant count-rate increase, of a steady state or dc signal type, is most readily detected by processing methods that are inefficient as regards spike detection. This report therefore treats the influence of signal processing on the statistics of transient detection in more detail than other topics. Although a number of observations made here concerning the statistics of transient detection are not specifically connected with a certain type of detection system, only delayed-neutron monitoring is discussed in detail, inasmuch as the use of fuel-failure monitoring for warning purposes is strongly emphasized in comparison with diagnosis. This does not necessarily imply an adverse judgment of the utility of the various other widely used types of cladding failure monitors.[5-7] Nevertheless, indications from such equipment, however valuable in connection with diagnostics or detection of incipient trouble, inherently lack the element of timeliness required of a device that is to give the fastest possible warning of a serious failure.

The feasibility of fast detection, and the credibility of inferences about the type and extent of the failure drawn from the information supplied by the detection and signal-processing equipment, depend in large measure on the detailed mechanism of failure. Much useful information on this topic may be expected to develop from the TREAT program and other tests; meanwhile, a discussion of failure mechanics, as provided in Section III, must be largely speculative.

The next question concerns the transport of fission products as well as debris injected into the coolant as a result of cladding rupture. Overall reliability of failure detection is considerably improved if a "close-in" site for the detector is technically feasible. For a loop site, reliability depends on the sampling efficiency of the loop intake manifold and can therefore be improved by design. The signal strength available from a failure is next determined by detection efficiency, which is both a function of the efficacy of moderation and the intrinsic efficiency of neutron detection of the sensing equipment. Finally, the stability and other qualities of the channel electronics, the design of filter circuits, and details of information-processing logic come strongly into play.

A more thorough treatment of the statistics of transient detection, from which certain results are quoted, has been issued as a separate report.[2] An investigation of sensing-equipment efficiency and background discrimination is provided for in the LMFBR program;[3] this subject and results of an earlier investigation are discussed in the appendix. Information-processing equipment for transient detection is available,[9] though this equipment may now be considered as obsolescent. The availability of monolithic logic circuitry has made a digital treatment system, with considerably greater reliability and freedom from maintenance problems, an attractive possibility.

The use of on-line computers, sometimes proposed for such tasks, inevitably is much more expensive if the cost of both software and hardware is included. Such use can be justified only where the computer is used intermittently, to perform several routines on a shared-time basis, or else is called on to perform a fairly complex calculation for which a special logic instrument would become comparably expensive. For continuous monitoring of one or two channels, a computer would be clearly inefficient; for correlating the fluctuations in a large number of channels, it would be very useful.

III. INJECTION AND TRANSPORT OF FISSION PRODUCTS IN THE COOLANT AFTER CLADDING FAILURE

In the following detailed discussion of various aspects of DNP monitor performance, which forms the bulk of this report, we shall begin with some observations on the injection, dispersion, and transport of DNP activities in the coolant.

The conjectural history of a possible cladding failure described below may turn out to be inaccurate in substantial detail when more is known about this subject and as new types of fuel pins are developed. Nevertheless, some of the general consequences of fuel failure that have a direct bearing on the strategy of detection should remain valid.

We shall then first suppose that the fuel, in the shape of a cylindrical rod, is bonded to the cladding by a layer of sodium that covers the top of the rod; the casing also contains some internal gas. The cladding may lose its integrity either through a leak in the gas region, or through a breach in the area covered by bonding sodium. The first breach may not be followed by any further weakening of the structural integrity, or alternatively be followed (possibly after some time) by further weakening and/or release of debris. Finally, the fuel pin itself may fracture and the entire structure disintegrate.

If the cladding fails in the top weld region, one would not expect any detectable DNP release since DNP species are halogens and thus tend to remain in the sodium. A signal from the gas-blanket monitor alone would thus identify this type of failure (provided that any other type of failure is reliably announced by the DNP monitor).

In contrast, a failure in the region of the sodium bond would be expected to result (possibly in addition to other effects) in the injection of DNP-contaminated bonding sodium into the coolant under pressure of the internal gas cover.

For present purposes, we are chiefly interested in the time dependence of this release, in comparison, say, to the time required for the passage of a small volume of coolant past the detection station. Evidently, the shape of the count-rate excursion will be determined by the passage time if release occurs over a much shorter interval, whereas the release should dominate the signal duration if the release occurs over a time which is long in comparison with the passage time.

The rate of release through a perforation depends on the shape of the perforation, viscosity, internal and external pressures, and external flow. Neglecting the shape or edge effect, which should not change results by more than a factor of two, we let A = area of perforation, p(t) = pressure of internal gas blanket, p_e = external pressure of flowing coolant against the cladding, and v(t) = velocity of efflux. On the basis of a simple energy argument,

$$A(p - p_e)\,dx = dmv^2/2 = wA\,dx\,v^2/2. \tag{1}$$

Hence,

$$v = \sqrt{2(p - p_e)/w}, \tag{2}$$

where w = bonding sodium density in g/cm^3 and dx = differential path along the streamline. Considering now the change dV in gas volume, we have, on one hand,

$$dV = Av\,dt, \tag{3}$$

while from Boyle's law,

$$dV = -p_0 V_0\,dp/p^2, \tag{3'}$$

where V(t) = gas volume at time t, V_0 = initial gas volume, and p_0 = corresponding initial gas pressure.

Combining the above equations and integrating, one finds the following straightforward relation between gas volume and elapsed time:

$$t = \frac{p_0 V_0 \sqrt{w/2}}{A p_e^{3/2}} \left\{ \sqrt{\frac{p_e V}{p_0 V_0}\left(1 - \frac{p_e V}{p_0 V_0}\right)} - \sqrt{\frac{p_e}{p_0}\left(1 - \frac{p_e}{p_0}\right)} + \sin^{-1}\sqrt{\frac{p_e}{p}} - \sin^{-1}\sqrt{\frac{p_e V}{p_0 V_0}} \right\}, \tag{4}$$

which can be expressed as the following power series for small values of the external pressure p_e:

$$t = \sqrt{\frac{w}{2p_0}}\left(\frac{V_0}{A}\right)\left\{\frac{2}{3}\left[\left(\frac{V}{V_0}\right)^{3/2} - 1\right] + \frac{p_e}{5p_0}\left[\left(\frac{V}{V_0}\right)^{5/2} - 1\right] + \frac{3p_e^2}{28p_0^2}\left[\left(\frac{V}{V_0}\right)^{7/2} - 1\right] + \ldots\right\}. \tag{5}$$

As a representative example, let

V/V_0 = 3 (threefold expansion of gas volume) result in an expulsion of the major portion of the bonding sodium, where we further assume

V_0 = 0.2 cm^3 (normal volume of internal gas),

p_0 = 3×10^6 dyn/cm^2,

p_e = 1.5×10^6 dyn/cm^2,

$$A = 0.01\ cm^2,$$

and

$$w = 0.9\ g/cm^3.$$

Equation 5 then yields a delivery time of about 1/30 sec. This value is sufficiently small to make the supposition that the expelled coolant initially consists of a slug of relatively small extension, carried downstream in the uncontaminated coolant, very reasonable for almost any fuel design. The spike signal this entails is evidently sharper for larger perforations; for a pinhole, edge effect increases the delivery time by a factor of 1.5 to 2. Still, the perforation must evidently be considerably smaller than 0.1 mm^2 to make t as large as 1 sec.*

As the contaminated slug is carried downstream, it mixes to some extent with the coolant. The detailed pattern of dispersion is not amenable to theoretical calculations, and can be established only through rather elaborate tests, optimally with a full-scale model. Such tests were carried out in connection with the design of RHAPSODIE and revealed a strong dependence of the dispersion, as well as mean transport velocity, on the location of the failure in the core. If this should be true for some other system, it could in principle allow one to derive limited information concerning the location of the failure from the detailed shape of the DNP detector signal--particularly for systems that feature divided flow into several heat exchangers. For present purposes, it may be stressed that for flow systems that do not contain extraordinary obstacles or other peculiarities, the rate of diffusion is much slower than the mean rate of transport. Therefore fission-product contamination tends to be contained in a relatively small volume as it passes the DNP detection station, whether the latter is sited on the main coolant duct or on a separate loop. The resultant temporary increase in the detector-channel count rate is thus expected to be of short duration.** In principle, a loop site allows stretching the signal by slower pumping or by widening the duct within the "field of view" of the detectors (i.e., inside the required moderating medium in which detectors are embedded). The rapid decay of DNP activities, however, makes the first of these measures inadvisable, while considerations of the efficacy of moderation make the second possibility somewhat doubtful. Consequently, the duration of the "signal" resulting from a sudden cladding perforation of sodium-bonded fuel is almost inevitably short, which has important consequences for electronic processing.

If nothing further happens in the core after breaching of one pin, the rate of DNP injection into the coolant will eventually reach some

*The effect of the external flow, neglected here, tends to speed up rather than retard the release rate.

**For the FERD system installed in EBR-II, this duration is estimated as between 0.3 and 0.5 sec.

equilibrium level. To estimate this, one would have to make detailed assumptions regarding the shape and extent of the leak; a small hole or fissure may delay the transport inside the cladding and across the perforation by an amount that reduces the level detection signal below threshold.

Suppose, however, that a flake of the cladding has become detached, whence a certain surface area of the fuel comes in direct contact with the flowing coolant. Then the equilibrium injection rate can be calculated in a straightforward way, and would be expected to result in a considerably stronger steady increase of the DNP detector mean count rate. This circumstance again appears to provide a certain measure of discrimination between types of failure. In the same vein, the detached flake, or possibly several pieces of debris, surface-contaminated with fission products, are expected to result in one (or several) particularly sharp spike signals in the "fast" DNP processing channel. This remark applies as well to fuel that does not contain bonding sodium; in that case, the cladding will be heavily contaminated with fission products by direct emission, as considered in Section IV. In general, solid debris is carried by a moving stream at a somewhat slower transport velocity, depending on size and shape. One would thus expect a series of separate spike signals from a number of pieces of debris, which would then point strongly to the described type of failure.

Discrimination between the DNP signatures of these different events is important in view of the relation of the degree of danger to the plant to the specific type of failure. The possible consequences of any failure in which large pieces of debris are thrown into the coolant are serious enough to make a plant shutdown mandatory upon discovery of such an event. In contrast, the cost of shutdown (and time-consuming search for the defective fuel element or subassembly) suggests a policy of continued operation if the failure is merely a perforation. This situation makes rapid diagnosis and discovery by any available and practical means an important matter and provides an economic incentive for research programs aimed at improved instrumentation.

The discovery of debris is even more strongly affected than the signal from the slug of bonding sodium by the sampling efficiency of the loop intake. This problem may be ameliorated by designing an efficient intake manifold, but can only be entirely avoided by siting the DNP detection station on a main coolant duct. Some other factors favoring such a site are discussed in Section VI.

Table I summarizes the subject matter discussed above.

TABLE I. Estimated Failure Signal from Certain Types of Fuel Failures[a]

Type of Failure	Fast DNP Signal (Spike)	Slow DNP Signal (Level)	Gas-blanket Monitor
Top weld leak.	None.	None.	Detectable (with delay).
Perforation in bond region.	Spike of short mean duration with "tail."	Weak, possibly undetectable.	Detectable (with delay).
Detached flake, leaving fuel directly exposed to flowing coolant.	Spike, followed by second sharp spike (without tail). Second spike reliably detected only by main duct sited DNP monitor.	Relatively stronger (probably detectable) signal, proportional to exposed area.	Relatively strong.
Several pieces of debris, flakes, etc.	Pattern of spikes, as above.	As above if coolant channel is not blocked; weak if channel is blocked.	Relatively strong.
Announcement delay.	5 sec or less.	20 sec minimum.	Several minutes (strong signal), 30 min (weak signal).

[a]Sodium-bonded fuel is assumed here; in the absence of such a bond, only detached flakes and other debris yield a fast and DNP signal.

A remark may be added concerning the prospects of fuel-failure monitoring with vented fuel pins. This concept evidently prevents detection through gas-blanket monitoring, largely through the buildup of long-lived activities in the blanket against which short-lived activities, characteristic of a wall perforation or weld leak, would be difficult to detect with reasonable efficiency. Delayed-neutron detection, on the other hand, is possible when the delay in the vent exceeds k half-lives of the longest DNP activity (about 1 min) for a core containing 2^k pins. For 4000 fuel pins, this is about 12 min, which appears to be still much shorter than delays considered by fuel designers. It follows that DNP fuel-failure detection is not seriously inconvenienced by vented fuel, assuming that the inherent gamma discrimination of the detectors is good enough to handle the additional gamma activity in the coolant. Some notes on available neutron detectors are added in the appendix.

IV. ESTIMATES OF SIGNAL STRENGTH

As discussed in Section III, the signal from a sudden failure is expected to be a sharp spike in the count rate, of a mean duration of less than 1 sec. On the other hand, the presence of bare fuel in the core (as an eventual consequence of a cladding failure) will yield a steady or dc level increase in the rate. It is therefore of interest to obtain a more quantitative estimate of the strength of these signals. A full-scale calculation involves specific design parameters, notably the flowrate and the distance from the detector site to the core. It is nevertheless instructive to estimate the signal strength semiquantitatively and especially to compare the strength of signals of spike and dc type. Because dc-type signals are frequently encountered in monitoring, there exists a widespread belief that such signals are more readily detectable than spikes, and electronic equipment may consequently be specifically adjusted for "dc level" detection. When a DNP channel is used primarily for failure diagnostics, as, for example, in the EBR-II installation, the comparative strength of the two types of signals thus becomes a significant question, quite apart from considerations of detection speed. As mentioned in Section III, the signal processing electronics can only detect either a spike or a dc signal efficiently; when only one processing channel is available, it must therefore be optimized for whichever signal is stronger.*

Let f = fission-rate density near the surface of a fuel pin of surface area S, R = fragment mean range in the fissile material, and a_k = fission yield of DNP species k; then the rate at which such DNP's are absorbed by the bonding sodium is $a_k fSR/4$. Normally, this rate equals the decay rate; hence,

$$N_k = a_k fSR/4\lambda_k \tag{6}$$

is the total number of species k DNP nuclei, of decay constant λ_k, in the bond. In addition to the direct-emission process, a certain amount of fission products may enter the bonding sodium through diffusion. This is negligible for EBR-II driver fuel, in view of the short half-lives of DNP's; as regards future reactors, the diffusion constants of halogens at elevated temperatures in uranium carbide are only poorly established. The actual amount of DNP enrichment of the bonding sodium could thus be higher by a largely unknown factor for special fuel operating at high temperatures.

As the cladding perforates, a fraction p of the bonding sodium is rapidly expelled and carried downstream, so that it reaches the detector site at time t_D after the event. With the somewhat schematic assumption of uniform detection efficiency e over the detector's field of view, comprising a duct volume V_d, and the further assumption of representative

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*A more practical system would use both types of processing, as considered in more detail further on in this section.

sampling--in a loop of flowrate F_ℓ--of a mainstream of flowrate F_0, one calculates a maximum spike count rate

$$R_{sk} = p(efSRa_k/4)(F_\ell/F_0)\exp(-\lambda_k t_D). \tag{7}$$

Following the rapid release of bonding sodium, we suppose that a fraction q of the fuel surface is now in direct contact with the coolant. DNP nuclei will thus be directly emitted into the stream, resulting in DNP enrichment of $fSRa_k/4F_0$. Integration over the detector yields a count-rate increase over background of

$$R_{\ell k} = q(efSRa_k/4)(F_\ell/F_0)\exp(-\lambda_k t_D)[1 - \exp(-\lambda_k V_d/F_\ell)]. \tag{8}$$

For a rapidly flowing loop, the quantity within the brackets can be expanded with negligible error, and one finds thus a ratio of spike signal-to-level increase rates of

$$\frac{R_s}{R_\ell} = \frac{pF_\ell}{qV_d}\frac{\sum_k a_k \exp(-\lambda_k t_D)}{\sum_k a_k\lambda_k \exp(-\lambda_k t_D)}. \tag{9}$$

For an instructive numerical example, we may take the FERD loop as a representative installation; this system has a volume V_d of about 2 liters and a loop flowrate F_ℓ of about 400 liters/min. Further, about one-third of the bonding sodium is assumed to be expelled in the spike and, rather schematically, one-tenth of the pin surface is assumed to remain in contact with the flowing coolant afterward. Taking delayed-neutron constants for ^{235}U from a standard compilation,[10] we find that the ratio given by Eq. 9 is about 90 for a delay t_D = 5 sec, and about 150 for t_D = 10 sec. For very long delays, where only the longest-lived DNP contribute significantly, the ratio increases toward three orders of magnitude. This calculation concerns a loop site; for a direct site, the ratio is apt to be larger, perhaps by a factor of two, since the flowrate is much larger while the detector volume viewed is also larger, though not in the proportion of the flowrate. DNP constants of the shorter-lived DNP species vary strongly with the reactor neutron spectrum and type of fissioning nucleus;[10] however, the values used here, for ^{235}U fast fission, are reasonably representative.

The assumption of a 10% bare fuel surface in contact with the streaming coolant is rather optimistic as regards the signal strength one can expect from a level-detection scheme. Small holes and cracks in single fuel pins are thus probably not detected by such a processing scheme, and an unmistakable signal could be due to several leaking elements or to a rather serious failure. Some discrimination is afforded here by longer-lived volatile fission products in the blanket, since the strength of that signal would vary somewhat like the number of open fuel pins.

The signals calculated above are superposed on a background that cannot be reduced below the level due to the presence of fissionables in the coolant. On one hand, uranium can adhere to the surface of fuel pins and other structural elements in the core; on the other hand, every fuel failure must be expected to throw some uranium into solution. The dissolved fissionables are, in turn, gradually removed through surface adhesion as indicated by experience with EBR-I. We may further suppose that patches of such surface adhesions could become detached and would thus produce spike signals as they pass through the detector. The relative strength of this false signal would depend on the thickness of the layer, i.e., on the amount of DNP's retained in it. Any plating process usually stops well before a layer of full-range thickness (about 10 mg/cm^2) is reached. Therefore the retention is expected to be small, and spike signal amplitudes due to release of adhesion, even of several cm^2 area, should be correspondingly weak in comparison to the bonding sodium signal. The level signal could, however, increase considerably because of retention of fissionables on core surfaces, which would be accompanied by a similar increase of volatile products in the blanket. This condition would then not only be difficult to interpret, but would also subject the detection of cladding failures through level increase to a large background.

All these admittedly largely qualitative observations point to the conclusion that the spike signal is considerably stronger than the level signal and moreover less interfered with by relatively slow fluctuations due to various natural causes. We must now further consider, however, the effect of purely statistical fluctuations. In principle, an instrument that can detect fast transients must respond to a fairly wide frequency band, whereas a level-reading instrument can have zero bandwidth. This consideration often leads to the conclusion that level detection must therefore be inherently more reliable, regardless of signal amplitude. The presence of natural fluctuations modifies this argument, as discussed in Section V.

V. DETECTION STATISTICS

The central purpose of detection-statistics calculations is to provide estimates of the reliability of measurements made with certain arrangements of equipment. The reliability of such estimates is another matter; generally, only qualitative assertations are possible.

Works on the statistics of detection of a "signal" in the presence of "noise," as these terms are usually understood, are largely concerned with recurrent signals within a well-defined frequency band. In contrast, the statistics of transient detection must consider a unique signal, while level detection is a matter of determining the first moment of a certain distribution whose higher moments constitute the noise. More specifically, we are here concerned with an input consisting of time markers (of negligible duration) arriving in a certain time sequence, for which one can presumably define a mean rate. Processing these markers in any convenient way, we wish to know whether any sudden change has occurred in the mean rate, or more precisely, with what reliability we can infer such a change from a certain type of processing (requiring a certain processing time). We are further given the information that one type of change in the mean rate is expected to last a short time (predictable within certain limits from the geometry of the flow system, and other parameters); the other type of change is supposed to be a permanent increase of the mean rate.

A. Level Detection with Cyclic Scaling

Consider, first, the detection of a change in mean rate or level; the simplest means of processing the input is a scaler accumulating counts over a fixed time t. The accumulated count is then recorded, the scaler reset, and the process repeated. In the absence of other information, we may first assume that the input time markers are purely randomly (Poisson) distributed in time. The Poisson distribution law allows us then to calculate the expectation (rms) value of fluctuations in the count in terms of the expectation value (mean) of the count itself. Moreover, the distribution law provides estimates of the probability that may be assigned to the assertion that a given count does, or does not, show an increase in the mean input rate. Tables and nomograms are available yielding probability assignments for various more elaborate combinations of counts. This imposing edifice, however, becomes unreliable to the extent to which the input distribution deviates from the Poisson law on which all these detailed calculations are based.

In the foregoing case, we have seen that the fissionable inventory in the coolant is apt to vary in a somewhat cyclic manner because of surface adhesion. The DNP detectors may also be sensitive to gamma pileup, which is dominated by the 15-hr ^{24}Na half-life. The total background thus varies in some manner with the detailed operating history of the plant; consequently a "dc-reading" instrument (e.g., a scaler accumulating counts over a very long time, or a computer that calculates long-term averages of such counts) cannot detect a level change due to fuel-element leakage unless such a change is considerably larger than the "natural" fluctuation amplitude. Put another way, one must restrict the integrating time of the readout to an interval over which natural fluctuations are small* and the Poisson law is therefore approximately valid. In principle, this implies either much shorter or much longer intervals than the natural cycles which yield the level fluctuations. In practice, however, much longer intervals may be several weeks, which becomes impractical if a continuous cleanup system is on line. The level-sensing processing routine thus amounts to a comparison of the count over t = 5 min to 1 hr with the average count over the preceding hour or several hours, the latter defining the average rate $\bar{R}_N$.

Applying statistical theory to this case, we may choose a numerical constant, m, as an index of reliability, such that a given count C can be subjected to the criterion

$$(C/t - \bar{R}_N)/\bar{R}_N^{1/2} \geq m/t^{1/2}, \tag{10}$$

which determines a certain probability for the assertion that this count signifies an increase in the "normal" mean rate, $\bar{R}_N$. The constant, m, simply gives the odds against the possibility that the above statement is false. From standard statistical tables, the odds are unity for m = 1, 4.64 for m = 2, 142.3 for m = 4, and 1.47×10^7 for m = 8, for example. Since such tables are based on the "normal law of error," the strictures suggested above apply here also.

The argument on which Eq. 10 is based may now be reversed. This leads to the observation that a possible increase R_S in the mean count rate $\bar{R}_N$ due to a sudden cladding leak cannot be detected in the available time t with a reliability given by constant m, unless this increase satisfies the inequality

$$R_S \geq m(\bar{R}_N/t)^{1/2}, \tag{11}$$

or

$$Q \geq m^2/t, \tag{11'}$$

*In terms of frequency, purely random (Poisson law) input has a "white" frequency spectrum, uniform from zero to infinity, on which cyclic fluctuations superpose local peaks. The input is still approximately random in regions well above or below such peaks.

in terms of the parameter

$$Q = R_S^2/\overline{R}_N. \tag{12}$$

As will be stressed repeatedly in the following discussion, Eq. 11' has a consequence of crucial importance in connection with hardware design: Any device, artifice, or processing routine that reduces the background rate R_N by some factor k improves overall reliability only if the signal response is reduced by less than $k^{1/2}$. For example, interposition of a shield between the coolant duct and the neutron detectors may seem like a good way of reducing the gamma-pileup background rate by a worthwhile factor (say an order of magnitude). If such a shield also reduces the delayed-neutron sensitivity by a factor of more than three, it evidently does more harm than good.

Returning to the statistics of detection after this digression, we shall now discuss the processing apparatus in more detail. As described above, processing requires not only a scaler, but also on-line digital computation equipment to establish the long-term average rate. Instead of a computer, one may use a digital count-rate meter (CRM), specially designed to perform this kind of operation; moreover, comparison of several independent channels may be employed to improve reliability, as described in detail elsewhere.[2,21] On the other hand, similar processing is readily available in the analog mode, at far less expense. Although digital methods have the advantage of greater stability, analog count-rate meters are more flexible and tend to have better statistics, as discussed below. Last but not least, analog count-rate meters have been widely used in reactor instrumentation and are therefore familiar to operating personnel.

B. Level Detection with Analog CRM

We consider now the statistics of level detection with a conventional analog CRM in which incoming counts are converted to standard charge pulses and pumped into a capacitor C; a bleeder resistor R, in shunt with the capacitor, allows the charge to leak away. Let E = voltage response to a single input count, and T_b = RC = circuit time constant; then the capacitor voltage changes as

$$F(t) = E \exp(-t/T_b) \tag{13}$$

for every input. Suppose again that the input is purely randomly distributed in time, at an average rate $\overline{R}_N$. Then the moments of the fluctuating capacitor voltage can be calculated by Campbell's or Carson's theorem. These theorems presuppose, however, not only that the input is Poisson-distributed, but moreover that the number $\overline{R}_N T_b$ is large enough to make statistics "meaningful"--another example of a rather qualitative and vague criterion of the reliability of statistical estimation. Campbell's theorem yields a second moment,

$$\lambda_2 = R \int_0^\infty F(t)^2 \; dt. \tag{14}$$

Now the CRM output must be displayed or processed further in order to communicate its information. Meters, chart recorders, etc., usually used for that purpose have mechanical inertia or damping requirements that act like an integration (low-pass filter) with time constant T_i. The second moment for the actual output thus comes to

$$\lambda_2 = E^2 R_N T_b^2 / [2(T_b + T_i)]. \tag{15}$$

The response to a sudden increase in the count rate (from R_N to $R_N + R_S$) is readily found to be

$$e(t) = E(R_N + R_S)\, T_b - ER_S T_b \frac{T_b \exp(-t/T_b) - T_i \exp(-t/T_i)}{T_b - T_i}. \tag{16}$$

From this equation, one further finds that the time $t_{0/90}$ required for the output to rise to 90% of its eventual level is $2.3T_b$ for $T_i \ll T_b$ and $3.9T_b$ for $T_i = T_b$, for instance. If one now again imposes the condition that this signal response be some multiple, say m, of the mean background fluctuations, one finds

$$\left.\begin{aligned} Q &= 0.975m^2/t_{0/90}, \qquad T_i = T_b; \\ &= 1.150m^2/t_{0/90}, \qquad T_i \ll T_b. \end{aligned}\right\} \tag{17}$$

Equation 17 is a somewhat more quantitative restatement of Eq. 11'. For example, the detection of a 3-pps signal in a 100-pps background with criterion $m = 4$ requires about 3 min, according to Eq. 17. A filter makes this time somewhat shorter (an advantage widely exploited in pulse-amplifier design, but generally ignored in connection with count-rate metering). The comparison of signal level and mean fluctuation does not, however, differentiate between large and infrequent (slow) fluctuations and small, rapid fluctuations. Actually, a level change is more readily detected in time $t_{0/90}$ if there are many individual excursions in that time, or if the mean time between such excursions is very long in comparison. The rate, r_0, at which the mean level is crossed in the upward direction by the processor output is predicted by statistical theory with about the same restrictive validity conditions as obtained for Campbell's theorem. That is,

$$r_0 = [\int(dF/dt)^2\, dt/\int F^2\, dt]^{1/2}\,(2\pi)^{-1}. \tag{18}$$

This yields an upward crossing rate

$$\left.\begin{aligned} r_0 t_{0/90} &= 3.9/2\pi, \quad T_i = T_b; \\ &= (2.3/2\pi)(T_b/T_i)^{1/2}, \quad T_i \ll T_b. \end{aligned}\right\} \tag{19}$$

Equation 19 shows that an "unfiltered" trace may deliver a more easily recognizable result. One is thus led to suggest the use of low-inertia chart recorders, yielding a large value of T_b/T_i.

Exactly the opposite policy is warranted if the trace level is fed to an alarm discriminator, which is readily triggered by fluctuations. For that case, one must consider the mean rate of fluctuations that exceed some level well above the mean, the so-called false-alarm frequency,

$$f_A = (2\pi\sqrt{T_i T_b})^{-1} \exp[-(R_A^2/R_N)(T_b + T_i)], \tag{20}$$

where the alarm level, A, is measured in terms of its equivalent mean incremental input rate, R_A. Evidently, $T_i = T_b$ is the best choice since it not only reduces the zero-crossing rate ($R_A = 0$) but also doubles the exponential factor.

As mentioned earlier in this section, the above equations fail where statistical theory becomes inapplicable. Equation 20 also breaks down, however, for very large values of the exponential factor, where the actual output-level distribution begins to deviate from the normal distribution on which the formula is based. A somewhat improved formula includes a correction term, consisting of a series of increasingly complex polynomial functions of rate and time parameters. This correction term, first derived by Edgeworth,[11] is chiefly useful in determining how far the simple false-alarm-frequency formula given above can be trusted.[2]

The level corresponding to R_A and the constant m evidently have a similar bearing on the minimum fuel leak rate which is actually detectable. The time required for detection must be short in comparison with fluctuations other than purely statistical ones. Such fluctuations imply deviations from the Poisson distribution on which the validity of Campbell's theorem rests. One must therefore take the measurement quickly enough to "ride" with slow fluctuations which cannot be smoothed by integration.

In addition to the cyclic effects considered above, slow fluctuations of the voltages and circuit-parameter values may affect the performance of an analog channel. Ultimately, the performance of a level-detecting, delayed-neutron, cladding-failure monitor channel can best be assayed experimentally, by exploring the amplitude and duration of all "natural" fluctuations and then setting thresholds accordingly.

C. Spike Detection with CRM

We turn now to the statistical aspects of the detection of a spike signal due to the sudden injection of bonding sodium or a piece of contaminated debris into the coolant. The duration of such a spike is essentially determined by the ratio of the length of duct viewed by the detectors to the lineal speed of the coolant through the duct. Realistic values of these parameters yield a mean spike duration of a fraction of a second. Although digital equipment can be readily designed to detect such a short transient, it is again more expedient to consider the performance of an analog CRM fed by the detector output. As in Section B above, we shall include the effect of filtering with a time constant, T_i, in addition to the CRM "bucket" time constant, T_b.

Treating the spike signal as a square pulse of duration T, for the sake of simplicity, we first determine the effect of the two time constants on the response. It is convenient, for that purpose, to calculate ratio M of the peak signal to rms fluctuation as a function of the ratio $y = T/T_b$. As before, we specify two cases: $T_i = T_b$ and $T_i \ll T_b$. This treatment becomes unreliable for values of y near unity, when one would expect the detailed shape of actual excursions to become important, but should be adequate for small values of y. An analysis of the simple circuit described above yields

$$M = \sqrt{2QT/y}\,(1 - e^{-y}), \qquad T_i \ll T_b, \tag{21}$$

and

$$M' = \sqrt{2}M \exp[-y/(e^y - 1)], \qquad T_i = T_b. \tag{21'}$$

For illustration, normalized responses $M/(QT)^{1/2}$ and $M'/(QT)^{1/2}$ are plotted in Fig. 1. This figure further includes the response of a circuit with a second clipping stage of equal time constant T_b. Such a circuit has the advantage of a very narrow bandwidth and is thus almost immune to any slow fluctuations in the input rate, due to causes discussed above. Finally, Fig. 1 shows the response of a simple digital CRM which stores each input for a time T_b and then dumps it. Figure 1 demonstrates that the statistics of transient response improve as the time constants are made comparable to the duration of the transient. As mentioned in the above paragraph, portions of the curves above the peaks are expected to be modified for actual transients, to the extent that such transients differ from the simple square-pulse model assumed here.

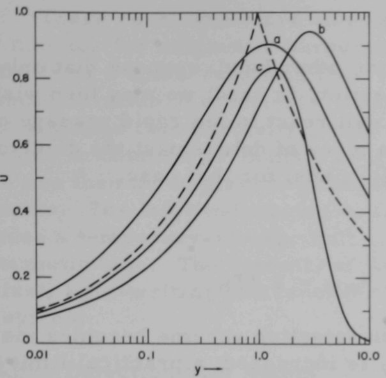

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Fig. 1

Normalized Filter Response to a Transient Signal of Duration T versus $y = T/T_b$. (a) For one clipping stage of time constant T_b; (b) for one clipping stage and one integrating stage with equal time constants T_b; and (c) for two clipping stages and one integrating stage with equal time constants T_b. (The broken line indicates the response of a digital CRM, described in Ref. 2.)

The result of these calculations may be simply expressed in a form analogous to Eq. 17. For a CRM with a single time constant, which is optimized for detection of a transient of duration T,

$$Q \approx 1.2M^2/T. \tag{22}$$

Except for a trivial difference in the numerical constant, the same result applies for other means of processing. Equation 22 gives the minimum signal count rate that can be detected in the presence of a certain background count rate with a certain reliability (determined by constant M).

D. Comparison of Level and Spike-detection Statistics

We are now in a position to compare the two kinds of signal: a count-rate level change due to a steady leak from a fuel element, versus a spike due to the sudden injection of a slug of DNP-enriched bonding sodium. The leak signal yields a minimum detectable Q given by Eq. 17', where the time $t_{0/90}$ is the integrating time, equivalent to the count interval in a digital processing system. Equation 9 gives the relative strength of the signals. For purposes of orientation, we take again the parameter values of the FERD installation and consider a delay $t_D \approx 10$ sec. The mean background rate is presumably identical for either case. Consequently, we find a ratio

$$Q_s/Q_\ell = 2.5 \times 10^3 (p/q)^2 \tag{23}$$

for the parameters Q_s and Q_ℓ appropriate for spike and level signals, respectively, in terms of the fraction p of bonding sodium expelled that effectively contributes to the transient peak, as well as the fraction q of bare fuel in direct contact with the flowing coolant. Combining this information with Eqs. 17' and 22, we obtain a ratio of reliability indices

$$M/m = 50(p/q)(T/t_{0/90})^{1/2}, \tag{24}$$

when each channel is optimized. On the other hand, suppose that only a slow channel, optimized for level detection, is used; we may then wish to ascertain to what extent this channel will react to the rapid passage of the bonding sodium slug or, perhaps, of a piece of debris past the detector bank. With Eqs. 21 and 23, one readily finds, for that case,

$$(M/m)' = 50(p/q)(T/T_b), \tag{25}$$

where T_b = CRM time constant; n.b., $t_{0/90} = 2.3T_b$.

As considered above, the level-detection scheme becomes more sensitive as the integrating time $t_{0/90}$ is increased; a practical limit to this integration is imposed only by "natural" fluctuations in the background rate. A maximum integration time of the order of 1 hr would appear a reasonable estimate. As concerns the transient duration T, geometry considerations indicate a rough value of 0.5 sec. This yields $(T/t_{0/90})^{1/2} = 1.2 \times 10^{-2}$ and $(T/T_b) = 3.2 \times 10^{-4}$. As concerns the other factor, $p = 30\%$ seems a conservative estimate for the fraction of the bonding sodium that contributes to the signal peak, while q might range from 1% to perhaps 10% for failures of various degree of severity. From these numerical estimates, one finds that when each processing system is optimized,

$$M/m \approx 0.6(p/q). \tag{24'}$$

Concerning detection of the spike signal by means of a level detector, optimized for level detection,

$$(M/m)' \approx 1.6 \times 10^{-2}(p/q). \tag{25'}$$

The above comparisons may be summed up in the following practical conclusions:

1. Where a DNP fuel-failure detection system is used primarily for diagnostic purposes, fast (spike) processing still yields more reliable detection of a failure than level detection (slow processing), when either processing system is optimized. Significant information of a somewhat different nature is obtained from either system, however; for that reason, both types of processing should be applied to the detector output.

2. If only a slow (integrating) processor is used, the spike signal is likely to be missed if that processor is optimized for level detection.

3. Processing time constants in the intermediary range, say a few minutes, are likely to result in unsatisfactory performance of the system with regard to either type of signal.

These conclusions are quite general with regard to the use of a DNP monitor for diagnostic purposes. They further emphasize, however, the utility of a spike-detecting DNP system for rapid warning. In view of the short duration of transients, such a system is not readily put together out of standard commercially available circuitry. In particular, it appears desirable to obtain a permanent record of the transient in digital form, which can then be displayed repeatedly with different processing time constants. The information-processing system provided for FERD thus includes a temporary-storage unit in which counts are directly written on magnetic tape. The contents of the store can be displayed by means of a fast, light-writing pen recorder.* Reference 9 describes details of this system.

E. Spike Detection with Alarm

We turn now to a brief discussion of the statistics of warning, in conjunction with a spike-detecting DNP monitor whose output is fed to an alarm discriminator. The essential purpose of an alarm system connected to a level-sensing processor, as considered in Section A of this chapter, is to call the attention of operating personnel (which may well be engaged by other instruments) to the DNP unit. The possibility of false alarms, given by Eq. 20 for that case, is therefore not crucially important; as discussed in connection with that equation, the false-alarm frequency can be readily reduced by filtering. In contrast, an alarm system based on spike detection may be connected to an automatic scram, supposing that the DNP monitor is designed to supplement flowmeter and other rapid warning instrumentation intended to limit damage in case of a catastrophic fuel failure. False alarms, in such a system, are certainly an extremely important consideration.

The false-alarm frequency is expected to depend on the alarm-level setting, system time constants, and prevailing background rate. It is expedient to express the alarm-level setting in terms of the detection probability for a real transient of certain intensity. In the treatment of level detection presented in Section A above, statistical fluctuations in the incremental (signal) rate were disregarded. For present purposes, a more realistic estimate results if one considers the development of the signal as a statistical process in which the number of counts delivered by the bonding sodium slug (or piece of debris) is assumed to vary in a completely random manner about a somewhat arbitrarily assumed mean. This treatment results in a statistical detection probability

$$g = \tfrac{1}{2}[1 + \Phi(G)], \tag{26}$$

*Feedback-potentiometric pen recorders, customarily used to display the output of count-rate meters, have inherent integration constants of the order of 1 sec and are thus (in view of Eqs. 21 and 21') not suitable.

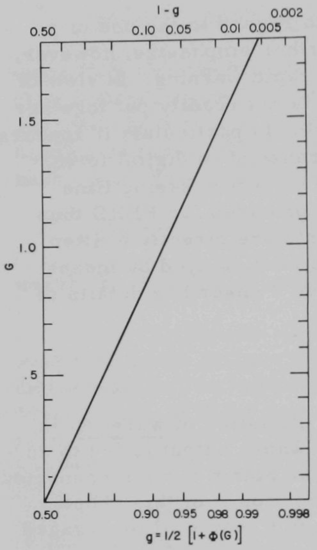

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Fig. 2

Alarm-level Parameter G versus Nominal Detection Probability g for a Transient-alarm System, Based on an Assumed Standard Transient Randomly Distributed about a Defined Mean Number of Pulses

plotted in Fig. 2, where

$$\Phi(G) = \frac{2}{\sqrt{\pi}} \int_0^G e^{-t^2}\, dt. \tag{27}$$

The parameter G is given in turn by

$$G = (R_S - R_A)\, T/\sqrt{2R_S T}, \tag{28}$$

where $R_S T$ = mean number of pulses in the transient, $R_A T$ = number of pulses which will just trip the alarm level. For a system featuring equal time constants $T_b = T_i$, one thus finds a false-alarm frequency f, as derived in Ref. 2, of approximately

$$f = (2\pi T_b)^{-1} \exp(-M'^2 H^2/2), \tag{29}$$

where

$$H(G) = 1 - G\sqrt{2/R_S T},$$

and G depends on the preset detection probability g through Eq. 26. The ratio M' is given by Eq. 21'. This somewhat cumbersome expression can be replaced by a more convenient expansion for values of $y \leq 1$. Moreover, Eq. 29 still requires a correction for the deviation of actual level distributions from exact Gaussian shape. This correction, first derived by Edgeworth,[11] is rather complex and depends on both Q and y.

Rewriting Eq. 29 explicitly in terms of Q and y, and including the Edgeworth correction term, E(Q, y), we have

$$f = (y/2\pi T)[1 + E(Q, y)] \exp[-(2QH^2Ty/e^2)(1 - y^2/12)]. \tag{29'}$$

We note that f is roughly proportional to y for small values of y. As y increases, the false-alarm frequency passes through a maximum value (evidently a particularly undesirable choice of y, in practice) and then declines sharply as the exponential factor makes itself felt. Except for the effect of the Edgeworth correction, to be discussed later in this section, the false-alarm frequency then appears to pass through a minimum as y increases beyond unity (which is evidently connected with the peak structure of the function M' as shown in Fig. 1).

To achieve the desirable goal of minimizing the false-alarm frequency while maintaining the fastest practical response, it is evidently not allowable to choose very small values of the parameter y, corresponding to large choices of the time constant $T_b = T_i$. Practical interest therefore focuses on the structure of the exponent, as well as on the Edgeworth term. Considering, first, the dependence of the exponent on y, we must again emphasize that the actual transient shape (hence the flow geometry, neutron moderation geometry, and location of neutron detectors) makes itself strongly felt for values of y near unity. For that reason, Eq. 29' probably underestimates the false-alarm frequency in that region. Concerning the factor H, we note that detection probabilities below about 95% are unacceptable in practice. On the other hand, detection probabilities above 99% result in only a negligible improvement of performance, at the cost of an unfavorable tradeoff between detection probability and false-alarm frequency. This consideration restricts the parameter G to values between about 1.2 and 1.7.

TABLE II. Effect of Signal Count Rate on False-alarm Frequency at Prescribed Detection Probability g

The calculated factor $H^2 = (1 - \sqrt{2/R_ST}\ G)^2$ appears in the exponent of the false-alarm-frequency formula given in Eqs. 29 and 29'.

	H^2	
R_ST	(g = 0.95) G = 1.2	(g = 0.99) G = 1.7
50	0.58	0.45
100	0.69	0.58
200	0.77	0.69

The detection-probability factor for representative values of the mean number R_ST of signal pulses in the transient is given in Table II, for purposes of orientation. The important inference from this table is that a large signal rate is desirable, other factors being equal.

The Edgeworth correction term, E(Q, y), contains various powers of the exponent and inverse powers of the number of background pulses R_NT_b. This correction thus becomes appreciable only when the exponent is large and R_NT_b is small, i.e., just in the region of interest. To achieve adequately low false-alarm frequencies, T_b must be chosen not much larger than the transient duration T. Therefore the correction depends essentially on R_N. For low background rates, E exceeds unity and rapidly becomes quite large as the exponent increases. Hence the false-alarm frequency becomes considerably larger than predicted by a simple formula that neglects the Edgeworth correction. The physical reason for this behavior is that the distribution at the CRM output is closely approximated by a Gaussian only in the vicinity of the mean level (where the exponent has small values), but deviates increasingly from a Gaussian for levels well above the mean. As the background rate increases, the distribution becomes increasingly Gaussian.

The predicted false-alarm frequency is plotted in Fig. 3, with assumed parameters as noted on the figure. This plot shows the serious

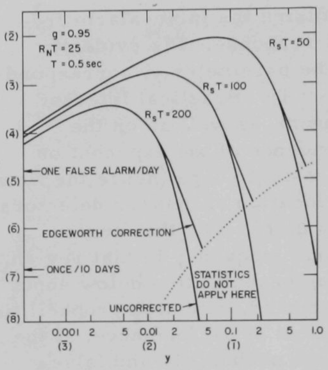

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Fig. 3

Predicted False-alarm Frequency in sec^{-1} (due to random background excursions) for a Transient-alarm System, Based on a Nominal Detection Probability of 95% and Fixed Background Rate, as well as Fixed Transient Duration. The three curves shown correspond to different mean numbers of pulses in the transient.

mistake one can make by neglecting the Edgeworth correction. The actual false-alarm frequency for a practical choice of time constants T_b is evidently not necessarily predictable by statistics, inasmuch as the actual distribution of the trace is not adequately described by the Edgeworth correction beyond a certain range of parameters. This circumstance provided the motivation for an experimental measurement of such distributions and associated false-alarm frequencies which is now underway. This measurement will take considerable time, but should eventually yield results from which one might hope to find a semiempirical formulation for the false-alarm frequency.

The above fairly straightforward statistical considerations imply that the performance of a transient detector improves with both signal and background input rate. The signal rate results in a larger exponential factor for a given required detection probability for a transient, while the background rate depresses the false-alarm frequency by making the distribution more Gaussian for large values of the exponent.

More generally, the performance of both slow and fast processors, with either visual or alarm-level-monitored output, depends on the detectivity, Q. This implies that an increase of both signal and background rates by a factor k actually improves performance by the same factor (in contrast to the supposition sometimes made that the signal-to-background ratio determines performance of counting equipment). Likewise, efforts to reduce the background are futile and in fact worsen equipment performance if they also reduce the signal by more than the square root of the reduction factor. That may be the single most important conclusion from this analysis of detection statistics.

The legitimate object of reliability improvement must be the strengthening of Q. Any means through which that goal might be achieved should be worth considering, and their cost must be carefully weighed against the possible cost of an undetected fuel failure. Section VI mentions some practical suggestions along this line.

VI. SITING OF THE DNP DETECTION STATION

The advantages of detection directly on a main coolant duct have been mentioned in several places in the preceding sections; it is perhaps useful to summarize such advantages here and further contrast them with some special advantages obtainable only from a loop site.

Considerations that favor a direct site include: (1) the shortest possible delay between occurrence and announcement of a serious fuel failure; (2) 100% sampling efficiency, thus making an event in which a few pieces of debris are thrown into the coolant unequivocally detectable; and (3) very good detection statistics, allowing a fairly reliable and extremely low false-alarm frequency, as discussed in detail in Section V.

There are, on the other hand, some drawbacks:

1. Detectors, signal cable, and other sensitive equipment are exposed to a higher temperature, and a considerably higher irradiation, than for a loop site. (Current-pulse amplification[13] can, however, circumvent the need for local preamplifiers.)

2. Routine maintenance on detectors may be difficult unless detectors can be located in reentrant straight channels, which then still would require massive shielding.

3. Neutron background from the core, specifically, is expected to require considerable attenuation through (at least) a shadow shield.

4. Space must be found not only for this shield, but for a local graphite stack which provides reasonably efficient moderation of delayed neutrons from a section of duct.

A loop site, on the other hand, can claim (in addition to better environmental conditions, easier maintenance, modest shielding requirements, and a readily implemented moderation assembly) the unique advantage of allowing <u>calibration</u> at any time by simply shutting the loop flow down and inserting a standard source (as provided for in the FERD system, for example). The background rate for no loop flow further allows one to determine the gamma background due to coolant activation alone and thus provides a ready check of the existing coolant contamination with fissionable matter. In conjunction with chemical analysis or mass-spectrometric analysis of coolant samples, this provides an estimate of surface adhesion in the core region.

The cost of loop systems that perform reliably must include the design of an efficient sampling manifold (absence of such a manifold is believed to be the worst feature of the FERD loop). This emphasizes the need for adequate lead time in designing the fuel-failure detection system. Other major cost items include a pump, flowmeter, heaters, and external insulation, and a lead radiation shield wherever the duct is exposed. A specially constructed section of duct through the graphite stack, with a vacuum heat insulation jacket, is desirable; this might resemble the sketch shown in Fig. 4. Finally, the entire moderator stack may require shielding, as was the case for the FERD system.

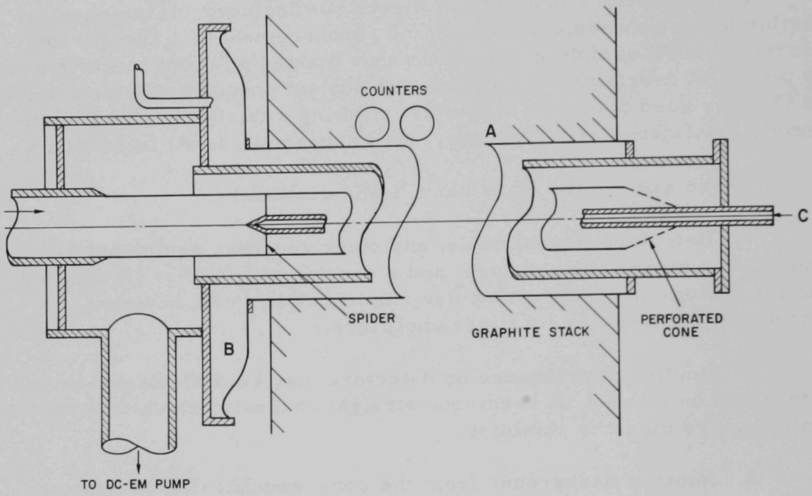

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Fig. 4. Reentrant Duct for Loop DNP Detector Station. The duct is surrounded by vacuum jacket A, for heat insulation; Bellows B allows for thermal expansion. Duct C allows insertion of a heating element for startup or standard source for calibration. Counters, indicated schematically, are placed close to the duct in a moderator (graphite) environment.

The cost of a direct site is not readily estimated, but is probably higher than a loop site, even when allowance is made for the pump ($20,000 for the rectifier and DCEM pump installed in FERD).

Table III summarizes these matters.

TABLE III. DNP Detector Siting Considerations

Criteria	I. CLOSE Site	II. LOOP Site
Delay	Shortest possible.	Longer.
Signal strength	High (weak decay enroute, long passage through detector field of view, total sample).	Low (stronger decay enroute, fast passage through detector, small and uncertain sample).
Background	Very strong; shielding essential.	Potentially down to coolant contamination.
Statistics	Favorable, in view of high count rates, allowing fast decision.	Poor; low count rates, fast decision doubtful.
Recognition of cladding and fuel debris	Favorable, from characteristic shape of fast spike signals.	Unfavorable because of uncertainty of sampling.
Major cost items	Shielding against core neutrons; radiation and heat-tolerant components; provisions for removal of instrument package.	DCEM pump; shielding of all ducts for personnel safety.
Maintenance	Foreseeably difficult.	Relatively straightforward.
Calibration	Not possible during reactor operation.	Any time, by shutting down loop flow.

VII. CONCLUSIONS

Fuel-failure detection in an LMFBR plant has two somewhat different objectives: (1) diagnosis of the failure, including type and degree of cladding perforation and eventual location of the failed element or its subassembly; and (2) rapid and effective warning of a major failure involving emission of debris, which in turn results in direct blocking of the coolant flow, or in the imminent danger of such blocking.

For objective 1, a variety of detection methods have been developed in connection with other types of reactor plants, among others, direct DNP monitoring of the coolant. For objective 2, only DNP monitoring in conjunction with flowmeters and similar devices that rapidly respond to the effect of a serious failure, has the potential of adequate speed of response.

This potential must, however, be developed by specific improvements in design. Some of these improvements also make a DNP monitor more useful for purely diagnostic purposes. It may become apparent, through some unforeseen development in plant design or instrumentation, that objective 2 can be adequately met by other means alone. Even if this should happen, improvements in the design of a DNP detector installation on one hand, and improvements in the art of information processing on the other hand, will strengthen the capability of DNP monitoring to provide more reliable detection as well as more discrimination between different types of failure.

In addition to reliability and discrimination, the principal requirement of objective 2 is speed. This calls for the design of a DNP detection station directly sited on the main coolant duct (or several such stations where the flow is divided). In contrast, a policy of primarily diagnostic use of failure-detection equipment may prefer a sampling loop. The design of such an installation is relatively straightforward; development of an efficient intake manifold is the principal problem to be solved. A direct site, however, is inevitably more reliable. On the one hand, sampling of possible debris is inevitably uncertain when the number of such pieces of debris is small. On the other hand, statistical considerations, discussed in detail in Section V, favor a detection location for which both signal and background are strong.

As regards optimization of the detection system, a direct site will mainly require improved gamma discrimination, while a loop site would need improved neutron sensitivity. As considered in the appendix, these requirements can be met by different types of detectors, which in turn require different electronics.

Processing of the count-rate signals delivered by the DNP-sensing channels requires equipment of the highest stability and reliability, designed specifically for fast delivery of a verdict upon the occurrence of a transient. This matter has received insufficient attention, for which reason it is somewhat emphasized in this review. Whether such processing is best effected by electronic equipment specifically designed for the purpose, or by programming a computer, is still a matter of divided opinion. Special equipment involves some development cost. A computer, on the other hand, requires considerable software, which may easily cost more than the hardware. Since the DNP monitor is presumably on line whenever the plant is in operation, the computer would be tied up most of the time. The requirement of a very large memory of short word length is also not readily met by commercially available digital computers. In principle, a computer would allow continuous correlation of a number of sensors and thus might reveal incipient danger, or help in locating fuel failures in the core. However, the detailed programming through which this desirable end might be realized is very uncertain at this time and defines yet another problem area in which work may be needed.

APPENDIX

Detection of Delayed Neutrons in the Presence of Activated Sodium

Delayed neutrons are emitted with quasi-Maxwellian energy distributions at mean energies of 400-600 keV. This makes fast-neutron detectors, which generally become effective only in the MeV region, unsuitable (even when the gamma background is not considered) and therefore makes moderation of the neutron energy spectrum mandatory. The strong gamma background now comes into play and makes hydrogenous moderators and beryllium equally unsuitable, since these media emit photoneutrons. The main decay radiation of 2.75 MeV of the ^{24}Na activity is above the photoneutron threshold of both ^{9}Be and ^{2}H (the latter being always present in natural hydrogenous media). Production of adequate quantities of dedeuterated hydrogen, which could then be loaded into zirconium (or similar hydrogen-occluding metals) or else fabricated into suitable radiation-resistant organic moderator (e.g., biphenyl), is possible in principle but probably too expensive. Thus, the only practical moderator is graphite. The nuclear parameters of graphite that come into play in moderation are sufficiently worse than those of hydrogen to require a rather large stack of graphite, which must be arranged in quasi-cylindrical geometry about the coolant duct. Calculations show that the optimum location of detectors is as close to the duct as possible; practically, however, each detector creates a void which interferes with moderation. At some point, an optimum tradeoff is thus reached.

Some of these matters were investigated when the FERD loop was designed. The test arrangements are described in Ref. 14. However, further investigations are desirable since the described tests were somewhat restricted by time and budget considerations. Widening of the duct in the moderator (which, for various reasons, was not deemed advisable for the FERD loop) may perhaps be reconsidered; a re-entrant duct, as sketched in Fig. 4, would offer certain advantages. Lengthening of the entire detection station, prevented in FERD by lack of space, would be a simple means of improving performance.

When the detection geometry has been set, there remains a choice between a number of different types of sensors, with different gamma rejection, neutron sensitivity, and heat and radiation tolerance. Gas pressure and detector size, shielding, electronics, and other variables provide further options. The dominant theme in this search is the achievement of an acceptable level of gamma background at the highest possible neutron-sensing efficiency. The gamma background is not only objectionable from the point of view of performance quality (as discussed in Section V), but moreover tends to vary with reactor operational history. Indeed, if an important gamma background component remains after the best available means of background reduction has been chosen, this would have to be measured in a separate channel and proportionately subtracted from the base level of the alarm discriminator or other indicating device. The following discussion therefore centers on background reduction.

Gamma radiation is only weakly absorbed by the gas in the counter; its effect is largely due to interaction with counter walls, principally Compton scattering, which results in recoil electrons. The differential scattering cross section for this process amounts to 300-550 mb/sr per electron in the 1- to 2.7-MeV energy range for forward scattering (within a few degrees), but drops off rapidly with scattering angle (60-100 mb/sr per electron at 20°). Table IV gives the energy of the scattered electrons for forward scattering for the two gamma rays emitted in ^{24}Na decay. In addition to that radiation, ^{24}Na is a source of Bremsstrahlung from the 4-MeV beta particles, and primary gammas are readily scattered and thus degraded in energy before they reach the counter. Table IV also gives the range in NTP BF_3 gas, and in aluminum, of electrons of forward-scattering energy.

TABLE IV. Properties of ^{24}Na Gamma Radiation of Interest to Counting in This Background

E_γ,	$\theta = \pi,\ \phi = 0$			$\theta = \pi/2$			
MeV	ϵ_r	$R(\epsilon_r)$	$R'(\epsilon_r)$	ϵ_r	$R(\epsilon_r)$	$R'(\epsilon_r)$	ϕ
2.76	2.52	160	0.18	2.33	140	0.16	14.70
1.37	1.16	66	0.07	1.00	59	0.065	21.30

Here, ϵ_r = Compton electron energy when photon is scattered through θ; ϕ = electron scattering angle (deg); $R(\epsilon_r)$ = range (in.) of recoil in BF_3 gas at NTP; and $R'(\epsilon_r)$ = range (in.) of recoil in aluminum.

The range in aluminum indicates that such electrons can start at considerable depth and still reach the counter gas; in fact, for a thin-walled counter, electrons can originate in scattering processes <u>outside</u> the counter. Because of this circumstance, the pileup can actually worsen if counters are wrapped in lead sheet, with the object of shielding. (Lead has a considerably larger Compton cross section than graphite.)

The range in BF_3 indicates, on the other hand, that only a small fraction of the electron's kinetic energy can be transformed into ionization before the electron strikes the opposite wall. The dominant effect of many such electron traversals is therefore a large number of pulses, individually much smaller than those released by neutron capture in the gas (cf. Tables IV and V). The observed pulse-height spectrum, however, will extend to considerably larger pulse heights than the mean pulse height, because (a) several small pulses can pile up at high input rates, and (b) occasionally a

Compton electron is scattered about inside the counter and thus delivers more energy. When the gamma radiation has an energy comparable to the energy release from neutron absorption, the pulse-height spectrum due to the gamma background may overlap the pulse-height spectrum generated by neutron capture. Gamma discrimination thus is a matter of degree, and must fail when the strength of the gamma source exceeds a certain limit.

TABLE V. Neutron-detection Parameters

Nuclide	Q, MeV	σ_{th},[a] barns	Products (energies, MeV)
^{3}He	0.764	5400[b]	^{1}H (0.572), ^{3}H (0.191)
^{6}Li	4.78	945[b]	^{4}He (2.05), ^{3}H (2.74)
^{10}B	2.79	4010[b]	93% ^{4}He (1.47)+^{7}Li (0.84)+γ (0.45); 7% ^{4}He (1.78)+^{7}Li (1.01).
^{235}U	~180	580	2 fragments (~60 and 90)
^{239}Pu	~180	740	2 fragments (~60 and 90)

[a]σ_{th} = cross section for neutrons of mean velocity 2200 m/sec.
[b]Cross section inversely proportional to velocity.

There are several means of raising this limit, for which a price generally must be paid in neutron-detection efficiency. A given installation thus tends to have an optimum tradeoff; and certain types of counters, in a certain geometry, with certain channel electronics, will result in the best neutron-detection efficiency at an acceptable gamma background. Another important consideration, however, is the stability of different types of sensors in continuous exposure to high temperatures and radiation levels, which may make some otherwise attractive choices unsuitable. In the rest of this appendix, some of the means through which the neutron-to-gamma count ratio can be improved are discussed under separate headings; usually a combination of such measures is most suitable.

1. Shielding

Each counter may be surrounded by a certain thickness of lead (or some other medium of high density, such as depleted uranium), or else the entire duct, as it passes through the graphite stack, may be covered with a shield. Unfortunately, significant attenuation of the highly energetic gammas emitted by the activated coolant requires a rather massive shield: the thickness needed for attenuation by a factor of ten amounts to 7 cm of lead or 4 cm of uranium. Assuming that the mechanical problems created by the weight of an effective shield can be solved, the effect of shielding on moderation and geometry, which tends to reduce the neutron-counting efficiency, must be carefully evaluated. As repeatedly stressed in the body of this report, any reduction in the neutron-detection efficiency, say by a factor k, must be accompanied by a k^2-fold reduction in background in order to do any good. The outlook for shielding is therefore pessimistic. If any other method of reducing the gamma background count still does not produce acceptable results, it may be necessary to shield, even though statistical performance becomes worse. A further possibility, which might be considered when everything else fails, is the use of enriched rather than depleted uranium, perhaps in addition to a shield. The graphite stack is thus converted into a neutron-multiplying assembly. Calculations indicate that a multiplication up to 20 is readily feasible and improves the neutron-flux distribution without seriously worsening detection statistics. (Fluctuations in the neutron count are increased by multiplication, an effect that is used in Rossi-alpha and similar measurements.)

2. Counter Geometry

In proportional counters filled with a neutron-detecting gas, neutron-detection efficiency varies with volume and filling pressure, while gamma background (cf. Table IV) varies with surface area. If every gamma-induced pulse were counted, one would obtain the lowest background by using a single large counter, with the highest practical gas pressure. Actually, the gamma background at the channel output is due to either pileup of a fairly large number of individual pulses, or to single Compton electrons which have been multiply scattered inside the counter. Concentrating, for the moment, on pileup, one can obtain an order-of-magnitude estimate from a drastically simplified model of this basically complex process; a more refined calculation would require considerable effort. Let each gamma absorption deliver a square pulse of duration T and height h to the amplifier, while the discriminator is set to accept all pulses above height H. For a pulse rate R (due to gamma absorption only), the resulting count rate is

$$c = \frac{R}{1 + RT} e^{-RT} \frac{(RT)^{j-1}}{(j-1)!} = \frac{j}{T} e^{-RT} \frac{(RT)^j}{j!(1+RT)}, \qquad (A.1)$$

where

$$j = H/h, \qquad (A.2)$$

and $(j+1)$-fold and higher-order pileup is neglected (in view of the rapid decline of the pileup rate with order).

The pulse rate R scales with wall area or counter radius:

$$R \sim r. \qquad (A.3)$$

Similarly, the height h of individual pulses scales with counter diameter and pressure, assuming that the amount of ionization deposited in the counter gas is approximately proportional to the track length. Thus,

$$h \sim pr. \tag{A.4}$$

We may now compare count rates for two arrangements of equal neutron sensitivity, first considering k small counters versus one large counter of equal total volume, all operating at the same filling pressure. Let primes denote the multicounter system; then the relation between total count rates is

$$R' = R\sqrt{k}, \tag{A.5}$$

and the order of pileup required to reach the discriminator bias H is

$$j' = j\sqrt{k}. \tag{A.6}$$

Inserting these relations in Eq. A.1, using Stirling's approximation for factorials, and rearranging, one finds the ratio of count rates to be

$$c'/c = c^{S-1}\sqrt{S}\left(T\sqrt{2\pi/j}\right)^{S-1}\left[1 + \frac{S(S-1)}{2}\,\frac{(RT)^2}{1+SRT} + \ldots\right], \tag{A.7}$$

where $S = k^{1/2}$. This equation shows that the background count rate is much lower for the multicounter system than for the single-counter system. As a numerical example, let $T = 0.1\ \mu\text{sec}$, $R = 4 \times 10^6$ pps, $j = 6$, and $S = 2$ (four counters against one). The pileup count rate then comes to about 164 cps for the single counter; the four-counter arrangement reduces this to 2×10^{-5} cps.

We next compare counters of identical neutron sensitivity at different pressures. Let primes now denote the high-pressure, small counter; then $r = kr'$, whence $p = p'/k^2$, $h' = hk$, and $R' = R/k$.

Proceeding as above, we now find

$$c' = \frac{c^{1/k}}{\sqrt{k}}\left(\frac{j}{2\pi T^2}\right)^{(k-1)/2k}. \tag{A.8}$$

If we insert the parameter values considered above, this predicts a count rate of about 3×10^4 cps for a half-size, fourfold pressure counter.

The margins of these predictions are so large that reversal of the judgment they imply through more refined calculations (including effects of electron scattering) is highly unlikely.

Equations A.7 and A.8 thus suggest the following effective measures for the reduction of gamma background in connection with active-gas counters: (a) many counters of small size and moderate filling pressure installed so as to face the gamma source with their smallest dimension; (b) counter types and associated electronics that yield the shortest possible pulse length; and (c) a neutron-sensing reaction that yields the highest available neutron pulse height, H. The last two suggestions are discussed below.

3. Neutron Detector Type

The number of strong nuclear reactions with thermal and epithermal neutrons resulting in emission of a charged particle is limited to those listed in Table V. Only ^{10}B and ^{3}He can be incorporated in a gas filling; the other nuclides must be applied as a surface coating. The above remarks on counter size and pressure specifically consider only active-gas fill, i.e., BF_3 and ^{3}He proportional counters. Table V indicates that the slightly higher cross section of ^{3}He is more than compensated for by its particularly low reaction Q value, which sets the discriminator bias H and thus the multiplicity of the pileup, according to Eqs. A.1, A.2, and A.6. These equations show that gamma discrimination with ^{3}He counters is a lost cause (as readily confirmed by use of these counters). Even in the absence of gamma background, the long-term stability of ^{3}He counters, particularly in a difficult environment, is considerably worse than that of BF_3 counters, as a matter of general experience. This type of counter is therefore practically eliminated from further consideration in connection with the problem under consideration.

BF_3 proportional counters are now available in a large variety of filling pressures, diameters, lengths, and anode sizes. Special counters of rugged construction and high quality of fabrication, with very good insulators, can be delivered. The main drawback of this type of counter is the relative length and fluctuation of the pulse risetime, which makes reduction of pileup through sharp clipping increasingly difficult beyond about 200 nsec. (Pulses of somewhat different risetime but identical height are turned into pulses of different height by clipping.) Counters filled to more than atmospheric pressure require a rather high polarizing voltage and generally have worse plateaus than low-pressure counters. Moreover, the gas tends to dissociate at high temperatures, and the released fluorine attacks the wall while boron is deposited on insulators. For these various reasons, BF_3 counters are not suitable for extreme environments.

Less neutron-detection efficiency is available from counters that have a boron deposit on the cathode. At the same time, such counters offer a particular advantage as regards gamma discrimination: With a low-pressure gas filling of a "fast" gas (such as methane), pulse risetime becomes remarkably short and clipping to less than 50 nsec is possible;

the gamma-discrimination possibilities of clipping are apparent from the above equations. The choice between many small counters and one large counter is again in favor of many counters, which evidently provide the largest wall area and hence the best neutron sensitivity. However, the limit is reached when the alpha range (of the order of 1 cm) becomes comparable to counter dimensions. Boron-wall counters are rugged and stable at high temperatures and require polarizing voltages roughly one-third to one-half of comparable BF_3 counter voltages.

For very strong gamma fluxes, one may have to resort to a lithium-coated counter, with a rather weak cross section but a very useful pulse height. Such counters are not available commercially and would have to be developed. Lithium fluoride coatings are readily evaporated or sputtered; either the triton or the alpha particle is readily counted.

Even more hostile environmental conditions may require fission counting. Although it has a better cross section, ^{239}Pu also has a prohibitively large alpha background and is therefore useless for large detectors. The discrimination against gamma radiation available from fission pulse chambers is far superior to that of any other detector, and can be further improved. Small plate spacing, not exceeding a few millimeters, and a high polarizing voltage can result in current pulses of 10- to 20-nsec duration, which evidently allow a spectacular reduction in pileup, provided that the channel electronics can process such pulses (as considered further in Section 4 of this appendix). The neutron-detection efficiency of fission chambers is limited by (a) a relatively small cross section, which drops rapidly to very low values in the epithermal region; and (b) the short range of fission fragments in the applied fissionable coating, which limits such coatings to a few hundred $\mu g/cm^2$ (range approximately 10 mg/cm^2). Thicker coatings result in integral pulse-height distributions with a strong slope (many fragments lose much of their energy in penetrating the coating); such pulse-height distributions eventually require more stability of the electronics than can be provided. Moreover, heavier coatings contribute largely small pulses, which are eliminated by the discriminator. To improve detection efficiency, it is thus necessary to increase the cathode area, usually through a multiplate structure. This, in turn, increases the device capacity. Before the advantages of current-pulse amplification[13] were realized, the largest practical capacity was about 200 pF; current-pulse amplification extends this limit, and also allows remote location of the preamplifier, as discussed in Section VI. Multiple-cell proportional counters could be constructed with a rather high efficiency per unit volume, but would be expensive to build and relatively fragile. Pulse ion chambers, which offer about three times the detection efficiency per unit volume of available commercial types, while delivering pulses of about half the length, can be readily designed.[14] The environmental conditions in which neutron sensors have to be used are likely to become steadily worse in future applications, not only in connection with failed-fuel detection, but also for flux and power level monitoring. A design and testing program would therefore appear to offer great potential benefits. It should be stressed that, in contrast to the availability of a great variety of BF_3 proportional counters, the design of commercial fission chambers offers little choice between a number of models that were originally used in conjunction with then-available slow electronics; no significant improvements have been made for the last 15 years.

4. Electronics

As pointed out in Section 3 above, the length of pulses has an extremely strong influence on the degree of gamma-background rejection of a neutron count channel. To exploit this possibility, amplifiers and discriminators with at least 100-MHz bandwidth are essential. Such circuits must, moreover, have low input noise and very good stability, both short-term and long-term.

Suitable current-pulse amplifiers[15] and discriminators of very good stability are available.[16,17] External feedback stabilization of an amplifier-discriminator[18] can effect further improvement, which in turn should make the use of counters with high sensitivity and somewhat poor plateau slopes realizable. Shape discrimination between electrons (from gamma absorption) and heavily ionizing particles (due to neutron absorption) has been advanced.[19] Improvements in the technology of field-effect transistors now allow input amplifiers with remarkable bandwidth yet low noise.[20] The outlook for significant improvements in electronic channels for neutron detectors is thus extremely favorable.

5. FERD Installation

A note may be added concerning the development of the FERD system detection equipment. The electronics originally provided were based on voltage-pulse amplification and thus required local preamplifiers using vacuum tubes; the main amplifier and discriminator was a transistorized, modular unit using transistor types then available. Overall bandwidth was about 40 MHz, allowing pulse-length reduction to 50 nsec. In a series of tests, counters of various types, exposed to mixed neutron and gamma radiation, were used as channel inputs, and different clipping and high-voltage options were investigated by running discriminator bias curves; some of this work was also done with conventional electronics. For fission chambers of Westinghouse type, a significant reduction in the gamma background was observed when pulses were clipped down to the limit imposed by the old-fashioned design of the fission chambers. As expected, BF_3 chambers yielded much less gamma discrimination, and plateau curves became unusable when short clipping was attempted; boron-lined counters provided much faster pulses, although worse plateaus with modest clipping, and under weak gamma irradiation, than BF_3 counters. As gamma irradiation was increased, and pulses shortened, the plateaus of boron-wall counters became only gradually worse and were thus far better than those of BF_3 counters under the strongest gamma irradiation available. The ^{24}Na gamma source for these tests was a quantity of ordinary salt, irradiated in the CP-5 reactor and then dissolved in distilled water; this source could be raised from a shielded container with gas pressure, into a standpipe. Neutrons were provided by using americium-beryllium sources and by placing a small bottle of heavy water into the gamma flux.

The scope of these tests was limited by time and budgetary considerations and used electronics that are now superseded. A new series of similar tests of neutron channels in strong gamma backgrounds would therefore be useful.

The gist of this appendix is summarized in Table VI.

TABLE VI. Neutron Sensors

Detector Type	Neutron Sensitivity	Gamma Discrimination	Environmental Stability	Availability
^{3}He admixtures	Highest.	Very poor; unusable except in mildest background.	Poor; deteriorates readily.	Only a few types offered.
$^{10}BF_3$	About 80% of equivalent ^{3}He counter.	Fair; useful to medium-strong gamma background.	Fair up to 100°C.	Many types, filling pressures.
^{10}B-coated cathode	About 50% of BF_3 counter filled to 1 atm.	Much better than BF_3; takes fairly strong background.	Fair up to 200-300°C.	Only a few offered.
^{6}Li-coated cathode	About 20% of ^{10}B-coated counter.	Order of magnitude better than ^{10}B-coated counter.	Fair up to 200-300°C.	None offered.
Fission chamber (standard)	About 2-3% of BF_3; depends on neutron spectrum.	Best available with commercial detectors.	Very good.	Several types, different environmental hardness, but essentially same design.
Fission chamber (special)	About 5-7% of BF_3 possible.	One to three orders of magnitude better than conventional fission chamber.	Very good.	Not available.

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